

*REWARD DENSITY AND VARIABLE-INTERVAL
SCHEDULE PERFORMANCE IN
AN OPEN ECONOMY*

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There is no general agreement regarding the form of the relation between response rate and reinforcement rate when single schedules of reinforcement are studied in an open economy. The present study assessed the form of this relation using reward density, which incorporates both reinforcement rate and duration of access to food, as an independent variable. Reward density was manipulated with 4 pigeons by changing the value of the variable-interval schedule, the hopper duration, or both. The relations between response rate and reward density were sharply rising and hyperbolic in 3 of 4 pigeons, replicating results obtained by Catania and Reynolds (1968). Because eating efficiency was lower in conditions that provided longer hopper durations, programmed reward densities differed from obtained reward densities. When response rates were examined as a function of obtained reward densities, the same relations were demonstrated more strongly. In further clarifying the relation between response rate and reward density in an open economy, these results lend support to the conclusion that open and closed economies yield different behavioral effects.

Key words: reward density, open economy, food hopper duration, variable-interval schedule, reinforcement rate, key peck, pigeons

The relation between response rate and reinforcement rate arranged by single schedules of reinforcement is fundamental in the experimental analysis of behavior, yet there is no general agreement regarding its form. Proponents of response-strengthening, economic, and behavior-regulation performance models all cite research to support their differing predictions of the form of the relation. The present experiment was an attempt to reconcile these differing interpretations of this important functional relation.

According to the response-strengthening view of Herrnstein (1970), the relation is sharply rising and hyperbolic and is predicted by a version of the matching equation adapted for single-operandum situations. With low rates of reinforcement, response rates rise sharply, but at higher reinforcement rates, response rates increase gradually and then reach asymptote (cf. Catania & Reynolds, 1968, Figure 1, especially Pigeons 278 and 279; Chung, 1966). Baum (1981, Figure 12) extended Herrnstein's analysis by predicting that the rising hyperbolic relations obtained

by Catania and Reynolds under variable-interval (VI) schedules would drop precipitously at very high rates of reinforcement.

Hursh (1978, 1980, 1984) proposed that the form of the relation between response rate and reinforcement rate depends upon the economic context in which it is studied, either open or closed. Hursh defined an open economy as "any of a variety of experimental arrangements that provides at least a measure of independence between daily responding and the equilibrium condition" (1980, p. 223). For example, an animal's body weight might be held constant at 80% of free-feeding weight either by supplemental feeding or by providing a fixed number of food presentations during each session. By contrast, he defined a closed economy as "an ideal state when daily consumption is the result of the equilibrium of supply and demand" (p. 223). That is, the total daily consumption of a reinforcer is determined solely by the organism's interaction with the reinforcement schedule. Hursh proposed that closed economies yield primarily an inverse relation between responding and rate of reinforcement with both interval and ratio schedules, whereas open economies yield primarily a direct relation. In inverse and direct relations, respectively, response rates decrease and increase as reinforcement rates increase. In addition to these primary differ-

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ences, Hursh (1980) presented data from prior research suggesting that a direct relation may occur in a closed economy when fixed-ratio (FR) requirements are high, resulting in low reinforcement rates (Collier, Hirsch, & Hamlin, 1972), and an inverse relation may occur in an open economy when FR requirements are low, resulting in high reinforcement rates (Felton & Lyon, 1966).

The behavior-regulation view of Staddon (1979), Hanson and Timberlake (1983), and Timberlake and Peden (1987) predicts a bitonic relation between response rate and reinforcement rate. A bitonic relation includes an ascending limb in which the relation between response rate and reinforcement rate is direct and a descending limb in which the relation is inverse. Timberlake and Peden proposed that a single bitonic relation occurs in both open and closed economies, thereby challenging Hursh's conclusion that different economies yield different relations: "It should be possible to produce both direct and inverse relations in both open and closed economies simply by manipulating the reward density" (1987, p. 37). Reward density is the percentage of total baseline eating duration per hopper access divided by the reinforcement schedule value (mean interreinforcement interval). During baseline, continuous access to the hopper was provided during 3-hr sessions, and actual eating duration was measured. If the hopper duration in a particular condition was 1% of the total baseline eating time and the reinforcement schedule was VI 20 s, a reward density of 0.05 (1/20) for that condition would result.

When Timberlake and Peden (1987) investigated a midrange of reward densities, from 0.0025 to 10 with FR schedules and 0.0021 to 3.33 with VI schedules, in a closed economy, inverse relations between responding and reward density were obtained. At a lower range of reward densities, from 0.001 to 0.5 with FR and 0.00021 to 0.033 with VI, in a closed economy, slightly bitonic relations between reward density and response rate occurred in 3 of 4 pigeons. When low reward densities, from 0.001 to 0.1 with FR and 0.000042 to 0.033 with VI, were studied in an open economy, relations were arguably bitonic in both pigeons studied under FR and in 1 of the 2 pigeons studied under VI, although data ob-

tained from the VI pigeons were unsystematic at the lowest reward densities.

Despite their differing conclusions, much of Hursh's (1980) data may be reconciled with those of Timberlake and Peden (1987). Both data sets show that increasing reward density decreased response rate in the closed economy at a midrange of reward densities. Timberlake and Peden's findings of slightly bitonic relations in 3 of 4 pigeons in the closed economy do not contradict Hursh's, because he did not use low reward densities and, as mentioned earlier, in fact noted that bitonic relations may occur in closed economies at the lowest reinforcement rates. Thus, the form of the relation between response rate and reward density in closed economies appears to be primarily inverse, but it may be direct at very low reward densities.

More variable functional relations between response and reinforcement rates have been obtained in open economies. Although Hursh (1980, 1984) concluded that open economies yield a direct relation between these variables, Timberlake and Peden (1987) observed that this relation in Hursh's open-economy data (1980, Figure 4) depended on a single data point obtained with a VI 20-s schedule. Were this point removed, Hursh's open-economy data would yield a flat to bitonic function. Although Timberlake and Peden concluded that open economies yield a bitonic relation between response rates and reward density, their data were variable. In their Experiment 4, of the 2 pigeons studied under VI schedules, the arguably bitonic relation of Pigeon VI 7535 also depended on a single data point at the 0.033 reward density. Without this point the relation would not be bitonic. The relation obtained with Pigeon VI 7239 included segments that were variable and direct, inverse, and slightly direct or flat, but did not represent a unitary bitonic function. These data, in combination with the hyperbolic relations between reinforcement and response rates consistently obtained by Catania and Reynolds (1968), suggest that the form of the relation between reinforcement and response rate in an open economy has not yet been established conclusively.

A further complication in determining the form of the relation is that of holding the percentage of total daily food intake obtained

in the session via contact with the reinforcement schedule constant across the different conditions. This was done in the open economies studied by Catania and Reynolds (1968, Experiment 1), Hursh (1978), and Hall and Lattal (1990), but not by Timberlake and Peden (1987, Experiment 4). In the latter study, all sessions provided 20 reinforcers, but because reinforcer durations varied across conditions, pigeons obtained differing amounts of food in the session across the different conditions. Varying the amount of food obtained in the session across conditions may affect response rate by yielding differing levels of deprivation within those conditions. Also, with varying amounts of postsession feeding in the different conditions (which would be necessary to maintain a 75% body weight), the possible substitution effects of supplemental food might vary across conditions. Both of these factors may influence response rates and therefore the form of the relation between them and reward density.

The present study further assessed the form of the relation between response rate and reward density in an open economy without the potentially confounding effects of variations in the amount of food obtained in each session. A wide range of reward densities was studied to determine the extent to which bitonicity occurs in open economies and to facilitate comparisons with the functional relations between response rate and reward density reported in the previously cited experiments.

METHOD

Subjects

Each of 4 male retired breeder White Carneau pigeons was maintained at 80% of its free-feeding body weight. Two had participated for 10 sessions in a study of response acquisition with delayed reinforcement, and 2 were naive. Each pigeon had continuous access to water and health grit in its home cage.

Apparatus

The experiment was conducted simultaneously in four nearly identical operant conditioning chambers, 30.5 cm long by 32.5 cm wide by 38 cm high. A response key (2.0 cm diameter) was located on the work panel 8.5

cm from the right wall and 25.5 cm from the floor of the chamber. The key was transilluminated by a yellow light throughout baseline and during all experimental conditions except when reinforcers were delivered. A minimum force of 0.15 N was required to operate the key. General illumination was provided by a white houselight during baseline and all experimental conditions. The houselight was off before and after each session during baseline and the experimental conditions, and when reinforcers were presented in all experimental conditions. Reinforcers consisted of varying lengths of access to mixed pigeon grain, depending on the pigeon and the condition, in a Lehigh Valley Electronics food magazine, the opening (6 cm square) to which was on the center of the work panel, 10.5 cm from the floor. A 28-V DC hopper light came on during food magazine operation. Magazine operation occurred when the pigeon's head was placed in the hopper during baseline and when reinforcement was presented during the experimental conditions. The hopper light remained on while the pigeon's head was in the hopper during baseline and for the scheduled hopper duration during the experimental conditions. A photocell beam was located in the food magazine, 2 cm from the front and 3 cm above the food aperture. A fan on each chamber provided ventilation and masked extraneous noise. The experiment was controlled from an adjacent room by a PDP/8®, a minicomputer using Super SKED® software.

Procedure

Each pigeon was trained to eat from the food hopper and was then exposed to a baseline condition. During the baseline condition, food was available continuously throughout five 3-hr sessions. Specifically, food was presented each time and as soon as the pigeon's head entered the hopper and broke the photocell beam. The hopper was lowered 3 s after the pigeon's head was withdrawn from the hopper. Eating duration was timed only while the pigeon's head was in the hopper. No more than one baseline condition was conducted on a given day. After each session in the baseline condition, each pigeon's body weight was allowed to return to 80%. On the day that body weight returned

Table 1

Percentage of total baseline eating time presented per hopper, variable-interval schedule value, and programmed reward density (RD) for each experimental condition.

	VI 13.3 s	VI 40 s	VI 120 s	VI 360 s
1.8% baseline		Condition A RD: 0.045	Condition C RD: 0.015	Condition F RD: 0.005
0.6% baseline	Condition J RD: 0.045	Condition B RD: 0.015	Condition E RD: 0.005	Condition H RD: 0.0017
0.2% baseline		Condition D RD: 0.005	Condition G RD: 0.0017	Condition I RD: 0.0006

to 80%, the next baseline session was conducted.

The experiment proper began following each pigeon's return to 80% body weight after the last baseline session. The experimental conditions are summarized in Table 1. Throughout the first nine conditions (i.e., Conditions A to I), programmed reward densities represented ratios of three hopper durations (1.8%, 0.6%, and 0.2% of total baseline eating time) and three VI schedule requirements (VI 40 s, VI 120 s, and VI 360 s). During these nine conditions, each successive hopper duration and VI reinforcement rate decreased by a factor of three. The five programmed reward densities were 0.045 (Condition A), 0.015 (Conditions B and C), 0.005 (Conditions D, E, and F), 0.0017 (Conditions G and H), and 0.0006 (Condition I). Condition J, implemented last, resulted from a VI 13.3-s schedule and a hopper duration that was 0.6% of total baseline eating time.

Each VI schedule was defined by a constant probability progression of 12 intervals, after Fleshler and Hoffman (1962), and each interval was selected randomly and without replacement. In conditions in which few intervals (5 to 10) were presented in each session, additional procedures were implemented to insure that pigeons received all intervals the same number of times in random order. This involved generating random sequences of 12 intervals, then using consecutive intervals from those sequences. For example, Pigeon 3987 received five reinforcers per session in Condition A. On Day 1 of this condition, the first five intervals from the first random sequence of 12 were presented. On Day 2, the next five intervals from the same sequence were presented. On Day 3, the last two intervals from the first sequence and the first three intervals from the second sequence

were presented. This pattern continued throughout Condition A.

Table 2 shows the condition order, experimental condition, programmed reward density, number of sessions, number of reinforcers, hopper duration, and amount of food consumed per hopper for each pigeon in each condition of the experiment. Amount of food consumed per hopper was determined by dividing the average amount eaten in the session for the last six sessions of each condition by the number of reinforcers in that condition. For each pigeon, the second through the fifth condition studied represented a descending sequence of programmed reward densities. For all pigeons, the two subsequent conditions represented programmed reward densities that were either ascending or held constant.

Each condition was in effect for a minimum of 10 sessions and was changed when the response rate was stable. Response rates were considered stable when the mean of the overall response rate (total responses divided by total time minus time spent eating) of the first and last three sessions of a six-session block was within $\pm 3\%$ of the mean overall response rate of those same six sessions.

Each pigeon's total daily intake was held at a fixed value to maintain its body weight at 80% of free-feeding weight throughout the experiment. If there was an increasing or decreasing trend in body weight, total daily intake was adjusted and maintained at a new value. In addition, the percentage of total daily intake obtained in the session was held roughly constant at 60% across conditions. The amount of food consumed in each session was measured, and if hopper duration was increased or decreased at the beginning of a condition, the number of reinforcers was adjusted so that each pigeon obtained about

Table 2

Condition order, experimental condition, programmed reward density, number of sessions, number of reinforcers, hopper duration, and amount of grain consumed per hopper (mean of the last six sessions) for each pigeon in each condition. In columns that show pairs of values, the first value corresponds with the first pigeon listed on the far left and the second value corresponds with the second pigeon.

Pigeon	Condition order	Experimental condition	Programmed reward density	Number of sessions	Number of reinforcers	Hopper duration (s)	Amount of grain (g) consumed per hopper
3987, 2662	1	A	0.045	53, 82	5, 9	7.0, 15.0	1.7, 1.1
	2	C	0.015	29, 23	5, 11	7.0, 15.0	1.9, 0.81
	3	F	0.005	12, —	5, —	7.0, 15.0	1.7, —
	4	H	0.0017	15, 11	10, 44	2.3, 5.0	0.73, 0.29
	5	I	0.0006	16, 11	22, 48	0.8, 1.7	0.38, 0.27
	6	E	0.005	40, 12	9, 20	2.3, 5.0	0.94, 0.52
	7	F, J	0.005, 0.045	14, 13	5, 20	7.0, 5.0	1.75, 0.56
1496, 7057	1	A	0.045	85, 90	6, 13	10.8, 28.4	1.7, 0.71
	2	B	0.015	16, 21	10, 16	3.6, 9.5	1.0, 0.53
	3	D	0.005	13, 21	23, 25	1.2, 3.2	0.47, 0.34
	4	G	0.0017	18, 35	20, 29	1.2, 3.2	0.54, 0.31
	5	I	0.0006	21, 12	22, 29	1.2, 3.2	0.48, 0.31
	6	E	0.005	13, 18	9, 14	3.6, 9.5	1.1, 0.57
	7	D, J	0.005, 0.045	14, 20	21, 14	1.2, 9.5	0.49, 0.63

60% of its total daily intake in the session. This was accomplished by trial and error across several sessions. The number of sessions required prior to determining the final number of within-session reinforcers for each pigeon at each condition is shown in Table 3 along with the average percentage of the total daily intake ob-

tained during the last six sessions of each condition. The first condition for each pigeon predictably required the largest number of sessions to obtain the target percentage of total daily intake and later conditions required fewer sessions to obtain the same criteria, with the exception of Condition E for Pigeon 3987. Six-

Table 3

Total number of sessions, number of sessions prior to determining final number of reinforcers, and percentage of total daily intake obtained in the condition (mean of the last six sessions) for each pigeon in each condition. In columns that show pairs of values, the first value corresponds with the first pigeon listed on the far left and the second value corresponds with the second pigeon.

Pigeon	Experimental condition	Total number of sessions	Number of sessions prior to determining final number of reinforcers	Percentage of total daily intake obtained in condition
3987, 2662	A	53, 82	27, 72	59.5, 64.3
	C	29, 23	0, 9	67.5, 58.0
	F	12, —	0, —	59.5, —
	H	15, 11	9, 2	61.3, 64.3
	I	16, 11	5, 4	64.0, 67.3
	E	40, 12	30, 4	63.2, 67.5
	F, J	14, 13	4, 0	63.3, 67.8
1496, 7057	A	85, 90	42, 68	56.8, 63.3
	B	16, 21	6, 8	63.3, 66.0
	D	13, 21	2, 9	62.2, 60.2
	G	18, 35	6, 13	59.2, 64.5
	I	21, 12	15, 0	65.0, 58.5
	E	13, 18	2, 4	65.8, 59.3
	D, J	14, 20	7, 0	62.8, 56.3

ty percent was the target, but actual percentages ranged from 56.3% to 67.8%. The average within-session percentage of total food intake across all conditions for all pigeons was 62.6%. After the number of reinforcers that provided about 60% of total daily intake had been determined on each condition, each session in the condition thereafter ended after this fixed number had been presented. The proportion of total daily intake not obtained in the session, about 40%, was provided by supplemental feeding in the home cage about 1 hr after the termination of the session. Session duration varied as a function of VI schedule value, number of reinforcers per condition, and rate of responding in the condition. Sessions ranged in duration from 208.16 s to 17,354.9 s.

In each condition, procedures were implemented to insure that pigeons contacted the programmed hopper durations. Timing of hopper duration began at the moment the pigeon's head entered the hopper aperture and broke a photocell beam. Timing continued only while the pigeon's head continued to break the photocell beam. If a pigeon kept its head out of the hopper for 60 consecutive seconds during a hopper presentation, the session was terminated. For Pigeon 7057 this occurred three times in Condition A. For Pigeon 2662, the session was terminated six times in Condition A and 20 times in Condition F. Eventually Condition F was discontinued for this pigeon because it failed to eat reliably from the hopper. Data from this condition were not included in the analysis that follows. No conditions were terminated for Pigeons 1496 or 3987.

After Conditions A through I (shown in Table 1) were completed, eating efficiency (defined as the average amount of food eaten per hopper presentation in the last six sessions of the condition divided by the hopper duration) was found to be negatively correlated with hopper duration for all pigeons (to be shown in the Results below). This finding suggested that the reward densities actually contacted differed from the programmed reward densities. To define the controlling variables more accurately, obtained reward densities were calculated by dividing the percentage of total baseline eating *amount* obtained per hopper presentation by the schedule value. Specifically, the average amount

eaten per hopper presentation in the last six sessions of each condition was divided by the total baseline eating amount, yielding a percentage. This percentage was then divided by the mean interreinforcement interval value in that condition to yield obtained reward density.

The ranges of obtained reward densities in Conditions A through I were 0.0022 to 0.09 (Pigeon 3987), 0.001 to 0.038 (Pigeon 2662), 0.0024 to 0.077 (Pigeon 1496), and 0.0015 to 0.03 (Pigeon 7057). Because the ranges of obtained reward densities for Pigeons 2662 and 7057 were too narrow to elucidate the form of the relation between response rate and reward density, Condition J (see Table 1) was implemented to expand the range of obtained reward densities for these pigeons. In Condition J, hopper durations and VI reinforcement rates for Pigeons 2662 and 7057 were one third of those that were in effect during Condition A. These short hopper durations were used to increase eating efficiency, which was expected to lead to higher obtained reward densities. The obtained reward densities for Condition J were 0.058 (Pigeon 2662) and 0.08 (Pigeon 7057).

RESULTS

Total baseline eating durations (mean of the five baseline sessions) were 388 s, 832 s, 598 s, and 1,575 s, and baseline eating amounts were 47, 73, 55, and 59 g for Pigeons 3987, 2662, 1496, and 7057, respectively.

Figure 1 shows the relation between mean response rates during the last six sessions of each condition and programmed reward density. Response rates were calculated by dividing the total number of responses by the length of the session, excluding eating time. The highest response rates of Pigeons 3987, 1496, and 2662 occurred at the highest programmed reward density. For Pigeon 7057, the highest response rate occurred at the highest and second highest reward densities.

Eating efficiency for the last six sessions of each condition is shown in Figure 2 as a function of hopper duration. For each pigeon there was an inverse relation between eating efficiency and length of hopper access. Due to these variations in eating efficiency across conditions, the pigeons did not come into contact

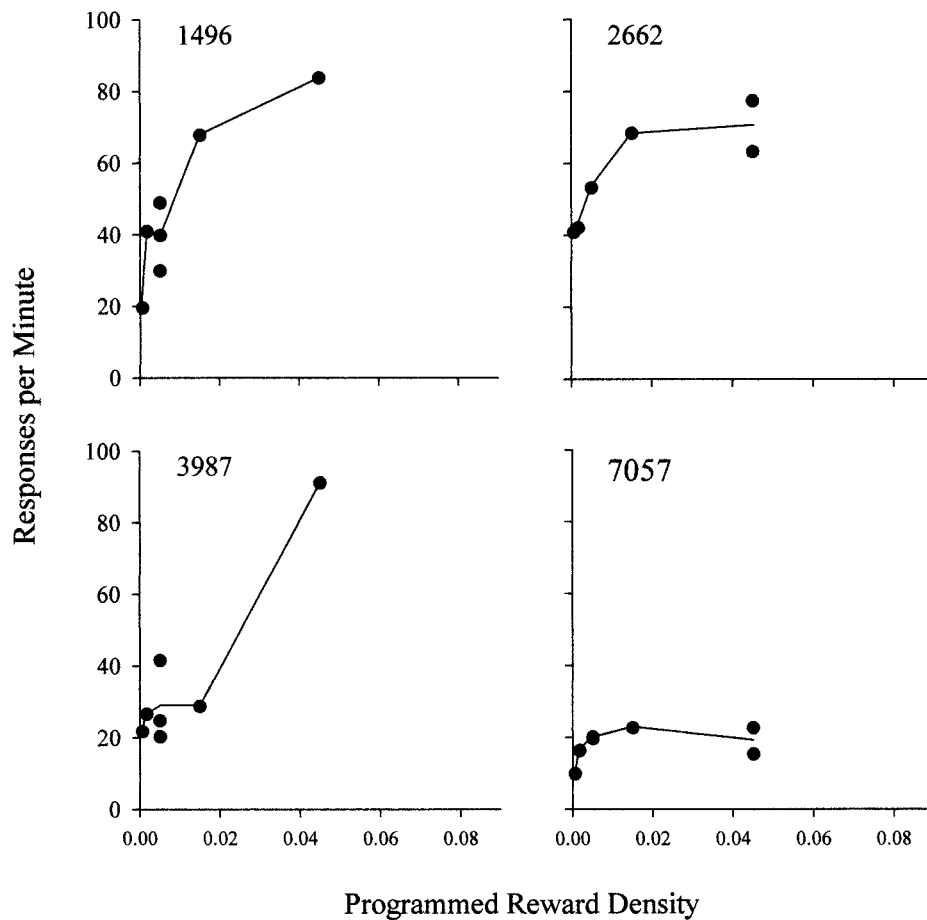


Fig. 1. Responses per minute as a function of programmed reward density for each pigeon. Each data point is the average of the last six sessions at each condition. For each graph, the line connects the data points or the average of the points where there are multiple data points at the same reward density.

with the precise reward densities that were programmed. For Pigeons 3987 and 1496, which had the briefer baseline eating durations, smaller baseline eating amounts, and generally shorter hopper access times, the percentage of baseline eating amount obtained per hopper exceeded the percentage of baseline eating duration presented per hopper in all conditions. As a result, these pigeons consistently obtained higher reward densities than the programmed reward densities. This effect was further magnified in conditions that provided the shorter hopper durations. For Pigeons 2662 and 7057, which had the longer baseline eating durations, larger baseline eating amounts, and generally longer hopper access times, effects were mixed. For Pigeon

2662, the percentage of baseline eating amount obtained per hopper exceeded the percentage of baseline eating duration provided per hopper in Conditions E, I, and J (which provided the shortest and second-shortest hopper durations), but was lower than the percentage of baseline eating duration in Conditions A, C, and H. As a result, Pigeon 2662 contacted lower reward densities than those programmed in Conditions A, C, and H, and higher-than-programmed reward densities in Conditions E, I, and J. For Pigeon 7057, the percentage of baseline eating amount exceeded the percentage of baseline eating duration in all but Condition A, which provided the longest hopper duration. This pigeon therefore contacted higher reward densities than

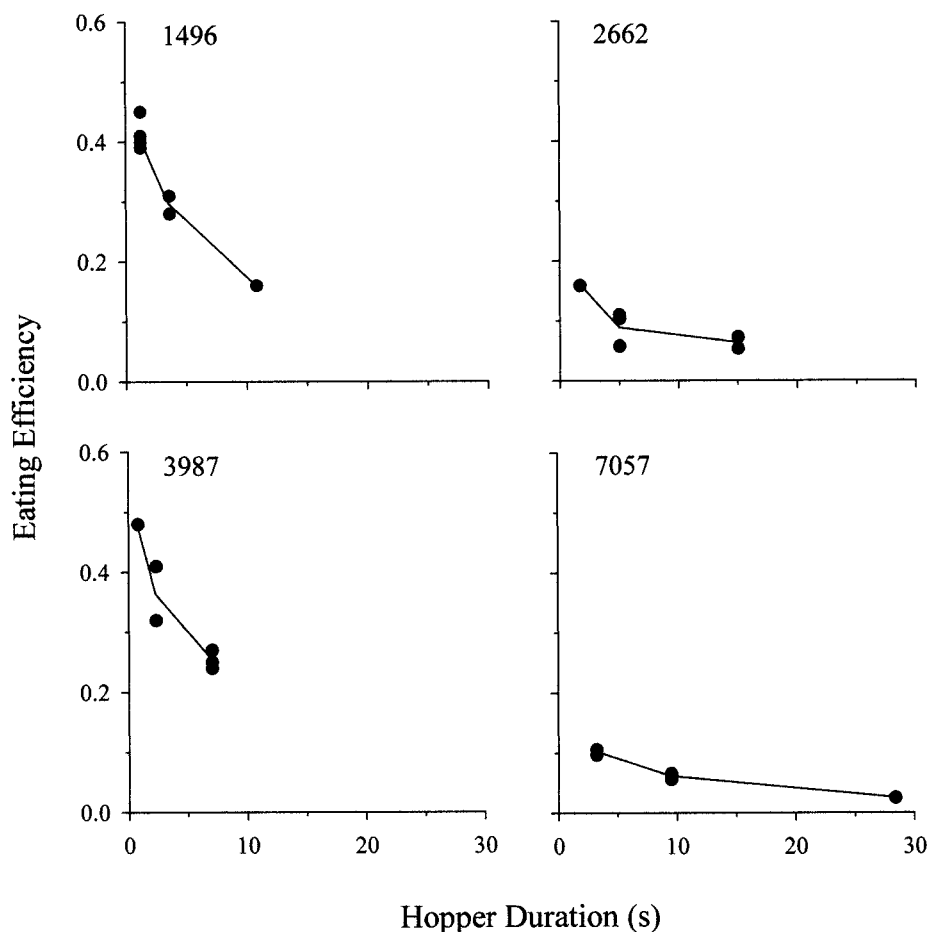


Fig. 2. Eating efficiency (the amount of food in grams eaten per hopper presentation divided by the hopper duration in seconds) as a function of the duration of access to the hopper for each pigeon at each condition. Each data point is the average of the last six sessions at each condition. For each graph, the line connects the data points or the average of the points where there are multiple data points at the same hopper duration.

those programmed in all conditions except Condition A.

Figure 3 shows mean response rates during the last six sessions of each condition for each pigeon as a function of obtained reward density. A comparison of Figures 1 and 3 shows that the ranges of obtained reward densities (Figure 3) were wider than those of programmed reward densities (Figure 1) for all pigeons. Excluding Condition J for Pigeons 2662 and 7057 (shown as the upper far right data points in Figure 1 and the far right data points in Figure 3), the ranges of obtained reward density for these 2 pigeons were narrower than the programmed ranges. Condition J expanded the ranges of obtained re-

ward density and clarified the relation between responding and programmed and obtained reward density for these pigeons. Excluding Condition J, the functions for Pigeons 2662 and 7057 were slightly bitonic. With Condition J, the overall relation between response rate and obtained reward density is more direct for Pigeon 2662 and flat for Pigeon 7057.

Several programmed reward densities were replicated using either the same or different combinations of VI schedules and hopper durations, with variable effects on response rates. These manipulations and their effects are summarized in Table 4. Conditions D and E yielded almost identical response rates for

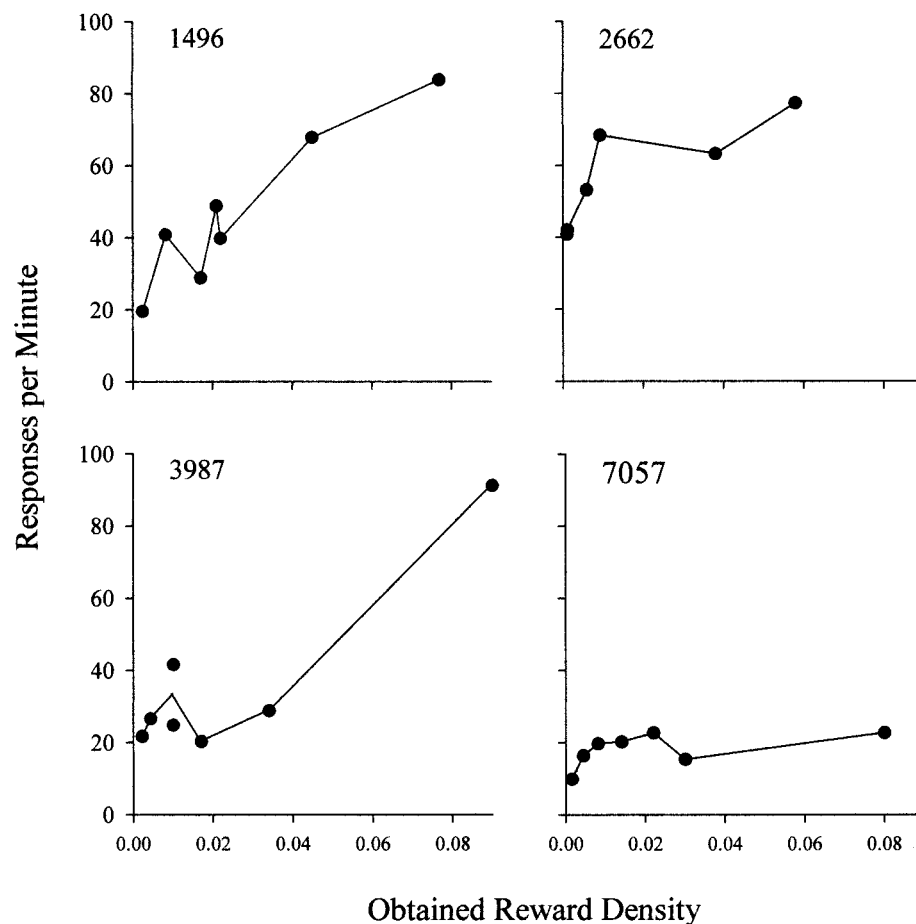


Fig. 3. Responses per minute as a function of obtained reward density for each pigeon. Each data point is the average of the last six sessions at each condition. For each graph, the line connects the data points or the average of the points where there are multiple data points at the same reward density.

Pigeon 7057. However, neither the same nor different combinations yielded closely similar response rates in any of the other replications.

DISCUSSION

The results shown in Figures 1 and 3 suggest that the relation between response rate and programmed and obtained reward densities is usually direct in an open economy within the ranges of reward densities studied. Responding increased with increasing reward density at the lower reward densities and increased more gradually or reached asymptote at the higher reward densities in 3 of 4 pigeons, although some variability occurred in the data of all 4 pigeons. The relations be-

tween response rate and obtained reward densities were direct and were not bitonic across the ranges examined for any of the 4 pigeons. This same direct relation occurred between responding and programmed reward densities, with the possible exception of Pigeon 7057, for which the relation arguably was bitonic.

The present findings provide only partial support for the indifference assumption of the molar behavior-regulation view. According to this assumption, the rate of responding is controlled by overall percentage of reward density rather than by reinforcement rate or duration alone. As described in the Results, responding primarily decreased when programmed and obtained reward densities were decreased by lengthening the VI schedule or

Table 4

Mean responses per minute for each pigeon during the last six sessions of conditions in which programmed reward densities were identical as a result of either direct or systematic replication of those densities. Conditions followed by an R indicate direct replications.

Pigeon	Condition	Programmed reward density	Variable-interval schedule (s) and percentage of baseline per hopper	Mean responses per minute
3987	F	0.005	VI 360, 1.8	41.6
	E	0.005	VI 120, 0.6	20.3
	F ^R	0.005	VI 360, 1.8	24.8
2662	A	0.045	VI 40, 1.8	63.3
	J	0.045	VI 13.3, 0.6	72.4
1496	D	0.005	VI 40, 0.2	48.8
	D ^R	0.005	VI 40, 0.2	39.8
	E	0.005	VI 120, 0.6	29.9
7057	A	0.045	VI 40, 1.8	15.4
	J	0.045	VI 13.3, 0.6	22.7
	D	0.005	VI 40, 0.2	20.2
	E	0.005	VI 120, 0.6	19.7

shortening the hopper duration. When reward densities were increased by shortening the VI schedule, increasing the hopper duration, or both, responding primarily increased. Thus, in most cases, the direction of change in responding was controlled by the direction of change in reward density, regardless of whether reward density was changed by varying the rate or duration of reinforcement. The indifference assumption further predicts that absolute response rate will remain the same when different hopper durations and schedule values are combined to yield the same programmed reward density. This aspect of the indifference assumption was not supported in the present study. As shown in Table 4, absolute response rates were not recovered when programmed reward densities were replicated using different combinations of VI schedules and hopper durations. However, it should be noted that absolute response rates were also not recovered when conditions were replicated exactly using the same combinations of hopper durations and schedule values.

Figure 4 compares the present results to those obtained in open economies by Timberlake and Peden (1987, Experiment 4, VI pigeons), Catania and Reynolds (1968, Experiment 1), and Hursh (1978, Experiment 2). Data are plotted as a function of programmed

reward densities because it was more feasible to estimate programmed than obtained reward densities in previous studies. Timberlake and Peden's results are shown as a function of actual programmed reward density because actual baseline eating durations and hopper durations had been presented. Data from Catania and Reynolds and Hursh are presented as a function of estimated programmed reward densities because the baseline eating times of their pigeons were not measured.

To estimate baseline eating times (as a step in estimating programmed reward densities), the average baseline eating time from the 4 pigeons in the present experiment (850 s) was used. This duration was obtained at 80% of each pigeon's free-feeding body weight, the same percentage used in the Catania and Reynolds (1968) study. The body weights of Hursh's (1978) monkeys were not specified, but Hursh noted that his open-economy conditions were designed to approximate those in which subjects are maintained at 80% body weight. Each hopper presentation in the Catania and Reynolds study was estimated to be 0.47% of baseline eating time, based on the 4-s hopper duration that occurred in all conditions of the study. The 0.47% value was divided by the VI schedule to yield an estimated programmed reward density for each condition. For instance, in their VI 108-s condition, 0.47 was divided by 108 to yield an estimated programmed reward density of 0.0044. In Hursh's experiment, each reinforcer presentation consisted of one food pellet. One food pellet was assumed to be roughly equivalent to a 2.5-s hopper duration. This estimate is based on a comparison of the number of reinforcers presented by Hursh and Catania and Reynolds in their open-economy conditions. In Hursh's study, 150 reinforcers were presented per session, with no postsession feeding. The reinforcers provided in each session accounted for the monkeys' total daily intakes. Hursh noted that this experimental arrangement constitutes an open economy because the amount of food obtained per session is held constant regardless of changes in the VI schedule or in response rates, thereby interrupting "any possible feedback between response rate and daily consumption" (p. 483). In Catania and Reynolds' study, 61 reinforcements (4 s each) were presented per session (for a total reinforcement time of 244 s), with an unspecified

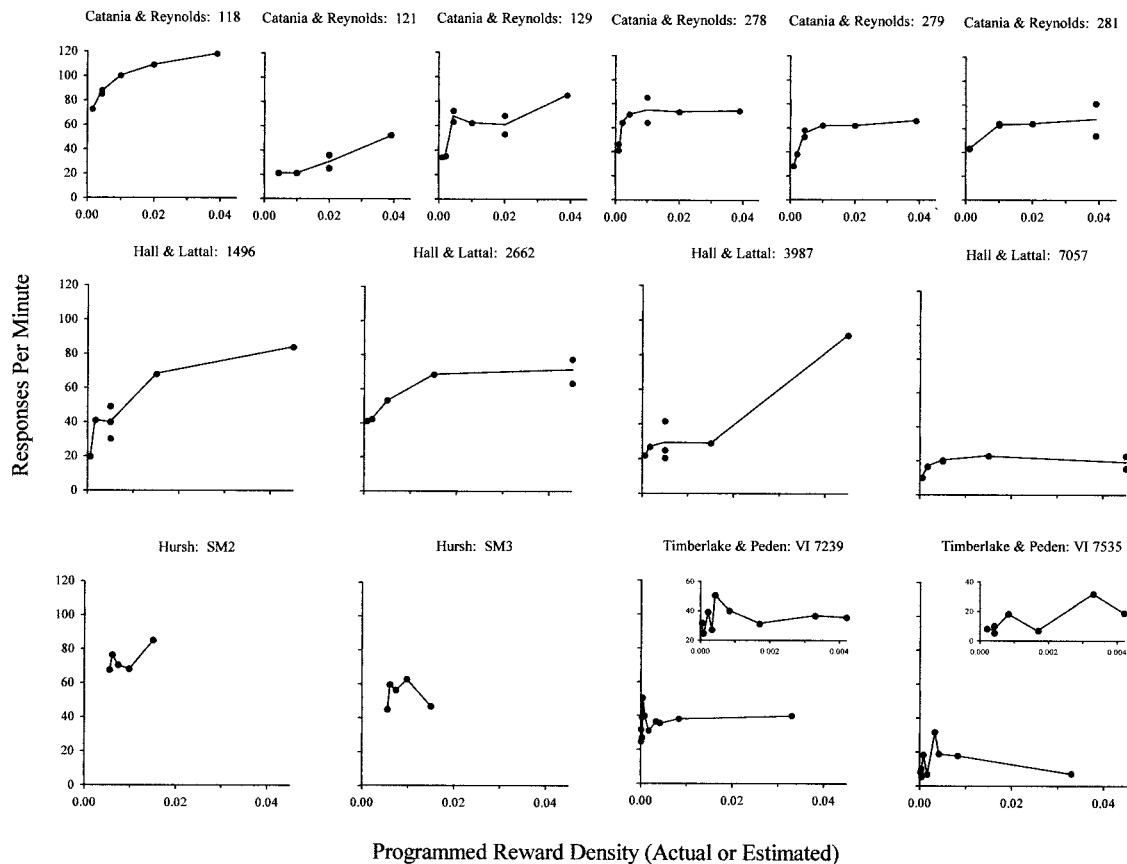


Fig. 4. Responses per minute as a function of programmed reward density, either actual or estimated, from subjects in experiments conducted by Catania and Reynolds (1968), Hursh (1978), Timberlake and Peden (1987), and the present experiment. The inset graphs expand the *x* axes at the lowest reward densities for the pigeons studied by Timberlake and Peden under VI schedules, thereby allowing closer inspection of data obtained at these reward densities. For each graph, the line connects the data points or the average of the points where there are multiple data points at the same reward density.

amount of postsession feeding. If Catania and Reynolds' pigeons received about two thirds of their total daily intake in the session and about one third via postfeeding, the total daily eating time may have approximated 375 s. This number divided by the number of reinforcers presented per session in Hursh's study, 150, yields 2.5. A 2.5-s hopper duration is estimated to be 0.294% of baseline eating time, again using the average baseline eating time of the 4 pigeons in the present experiment (850 s). This estimate of baseline eating time was divided by the average VI schedule in each condition to yield estimated programmed reward densities for Hursh's study.

The ranges of programmed reward density used in the present study and those presented

to the VI pigeons in Timberlake and Peden's (1987) Experiment 4 overlap sufficiently to permit a comparison of the relations obtained. In the present study, the range for all 4 pigeons was 0.0006 to 0.045. In Timberlake and Peden's study, the ranges were 0.00083 to 0.033 (Pigeon VI 7535) and 0.000042 to 0.033 (Pigeon VI 7239). In examining the relation for Timberlake and Peden's Pigeon VI 7535, the data show a variable but increasing trend from the second- to the fifth-lowest reward densities, as shown in Figure 4. The inset graph permits a closer inspection of these data by expanding the *x* axis at the lowest reward densities. Specifically, response rates in the two conditions at 0.00042 (the second-lowest reward density) were about 5.2 and 10.0 per

minute. Responding then increased to 18.2 at 0.00083 (the third-lowest reward density), decreased to 6.7 at 0.0017 (the fourth-lowest reward density), then peaked at 31.7 at 0.0033 (the fifth-lowest reward density). After the point of peak responding, an inverse relation between responding and reward density occurred at 0.0042, 0.0083, and 0.033 (the three highest reward densities). Overall the relation is variable, but is arguably bitonic. At the location of peak responding for Pigeon VI 7535, data from all 4 of the present pigeons show the early (low) portion of direct relations between response rate and reward density. This is a different relation from that obtained by Timberlake and Peden's Pigeon VI 7535.

The data obtained from Timberlake and Peden's (1987) Pigeon VI 7239 show variable but increasing response rates at the five lowest reward densities, as shown in Figure 4. Again, the inset graph provides an expanded view of data at the lowest reward densities. The inset graph shows that peak responding (about 50.5) occurred at 0.00042, the fifth-lowest reward density. An inverse relation then occurred from the point of peak responding across 0.00083 and 0.0017 (the next two increasing reward densities), and a direct or flat relation occurred from 0.0017 across 0.0033, 0.0042, 0.0083, and 0.033 (the next four increasing reward densities). These different segments do not appear to constitute a unified bitonic function. When the range of reward densities that overlaps between Pigeon VI 7239 and the present study (0.0006 to 0.033) is examined, the data of Pigeon VI 7239 show an inverse, then direct or flat relation, whereas data from the present pigeons show primarily a direct relation.

The present results also may be compared with those of Catania and Reynolds (1968, Experiment 1). Their ranges of estimated programmed reward densities were 0.0011 to 0.039, and overlap entirely with the range (0.0006 to 0.045) used in the present study. Data from Catania and Reynolds and the present study both show direct relations between response rate and reward density across the same reward densities. In addition to being direct, these relations also are sharply rising and hyperbolic in 5 of 6 of Catania and Reynolds' pigeons and 3 of 4 of the present ones. Thus, the present study replicates Catania and Reynolds' findings using reward density (which in-

corporates both VI schedule value and hopper duration) as the independent variable rather than VI schedule value alone.

A further comparison can be made between the present results and those of Hursh (1978). In his Experiment 2, the range of estimated programmed reward densities for Monkeys SM2 and SM3 was 0.0055 to 0.015. This range is included within the range used in the present study. The data from Monkey SM2 suggest a direct relation between response rate and reward density, and those from SM3 suggest a bitonic relation. It is possible to argue, however, that the form of each of these functions depends upon a single data point. If the data point corresponding to the highest reward density were removed, the relation for Monkey SM2 might be viewed as bitonic and the relation for Monkey SM3 can be seen as direct. Because data from open economies often appear to be variable, it seems that a wider range of reward densities is needed to determine the form of these relations more conclusively. Across the reward densities used by Hursh, data from the present study show primarily direct relations. The present findings therefore replicate those obtained with one of Hursh's subjects, Monkey SM2.

More recently, Zeiler (1999) compared the effects of several different programmed reward densities on random-interval schedule performance of the same pigeons in both open and closed economies. Like Hall and Lattal (1990), Zeiler found that response rates decreased with increasing reinforcement rates in the closed economy but those rates increased with increasing reinforcement rates in the open economy. It was not possible to determine reward density in Zeiler's experiment because the hopper duration varied from session to session to maintain each pigeon's body weight. Although this latter observation limits the direct application of Zeiler's findings to the general position set forth here, his results are, in general, consistent with this position.

Overall, the present findings replicate those obtained by Catania and Reynolds (1968) with all pigeons and Hursh (1978) with 1 monkey, but they differ from results obtained by Timberlake and Peden (1987) with both pigeons. In accounting for the similarities and differences across studies, certain methodological considerations may be relevant. As mentioned earlier, the percentage of total daily intake ob-

tained in the session was held constant across conditions in the present study as well as in the studies of Catania and Reynolds and Hursh, but varied in that of Timberlake and Peden (1987). For instance, the amount of food obtained in the session by Timberlake and Peden's Pigeon VI 7535 varied from a high of 34.8 g (with a hopper duration of 16.5 s) to a low of 1.2 g (with a hopper duration of 0.8 s). For Pigeon VI 7239, the amount varied from 66.6 g (with a hopper duration of 27.0 s) to 1.0 g (with a hopper duration of 0.3 s). In the present study, as noted above, each pigeon received about 60% of its total daily intake in each session. Varying the percentage of total daily intake obtained in the session across conditions may produce different behavioral effects from that of holding this percentage constant. Possible variables that might produce such effects are varying amounts of satiation in the different conditions and differing amounts of supplemental food provided to subjects after completion of the session, which may substitute for food obtained in the session via interaction with the reinforcement schedule.

Another methodological feature that may be relevant is hopper duration. One of the hopper durations used by Timberlake and Peden (1987) with Pigeon VI 7239 was very brief (0.3 s), raising the question of whether that pigeon actually obtained food each time the hopper was presented. Across the six lowest programmed reward densities for that pigeon (from 0.000042 to 0.00083), the lowest response rates occurred in the three conditions presenting the 0.3-s hopper duration. Because these conditions employed three different VI schedules (VI 30 s, VI 120 s, and VI 240 s), hopper duration rather than specific reward density was associated with low response rates. If the 0.3-s hopper duration contributed to these low rates, it also may have contributed to variability in the data across the six lowest reward densities. The two peaks in responding within that range (one of which was the overall peak in responding for the relation) occurred in conditions that provided somewhat longer hopper durations (1.35 s and 2.7 s).

The results of the present study have implications for the distinction between open and closed economies. Previous findings of Collier et al. (1972), Hursh (1978, Experi-

ment 1), Timberlake and Peden (1987, Experiments 1 and 2), Hall and Lattal (1990), and Zeiler (1999) generally agree on the relation between response rate and reinforcement rate (which can be expressed as estimated reward density) in closed economies. In all cases, the relations obtained in closed economies have been primarily inverse. In open economies, data from previous studies (Catania & Reynolds, 1968, Experiment 1; Hall & Lattal, 1990; Hursh, 1978, Experiment 2; Zeiler, 1999) suggest direct relations, although variability in the data has detracted from the conclusions. Only Timberlake and Peden (1987, Experiment 4) did not obtain direct relations in an open economy, but, as mentioned above, their relations are difficult to interpret. The present study replicates findings obtained by Catania and Reynolds, showing not only direct relations but relations that are sharply rising and hyperbolic across the range of reward densities studied. These relations are demonstrated most clearly when the data are plotted as a function of obtained rather than programmed reward density. In further clarifying the form of the relation between response rate and reward density in an open economy, the present findings lend support to the conclusion that open and closed economies yield different behavioral effects.

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